Interstellar Organics, the Solar Nebula, and Saturn's Satellite Phoebe

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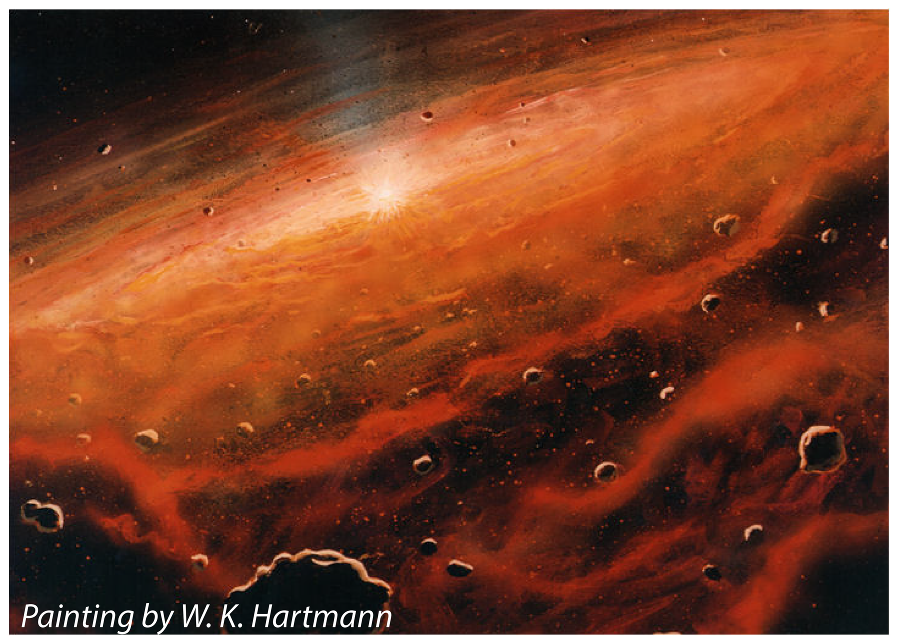

Star formation and the subsequent evolution of planetary systems occurs in dense molecular clouds, which are comprised, in part, of interstellar dust grains gathered from the diffuse interstellar medium (DISM). Organic material in the DISM was likely incorporated into the solar nebula, providing the feedstock for all the planets, satellites, and smaller icy bodies in the region outside Neptune's orbit (transneptunian objects, TNOs). In this work we trace an inventory of organic material from the Solar System's nascent molecular cloud to a satellite of Saturn, Phoebe, and then to the surface of Iapetus.

Phoebe (mean diameter 213 km) originated in the TNO region and was captured as a retrograde satellite of Saturn (Johnson and Lunine 2005). A recent collision on Phoebe released a quantity of dust that formed a ring in the satellite's orbit (Verbiscer et al. 2009), forming a source of small particles that spiral inward toward Saturn (Tamayo et al. 2011). These particles impact the next two satellites in the direction of Saturn, Iapetus and Hyperion, depositing low-albedo material that carries a distinct spectral signature of both aromatic and aliphatic organic molecular material. That spectral signature was detected and mapped on Phoebe, Iapetus, and Hyperion by the Visible-Infrared Mapping Spectrometer (VIMS) on the Cassini spacecraft.


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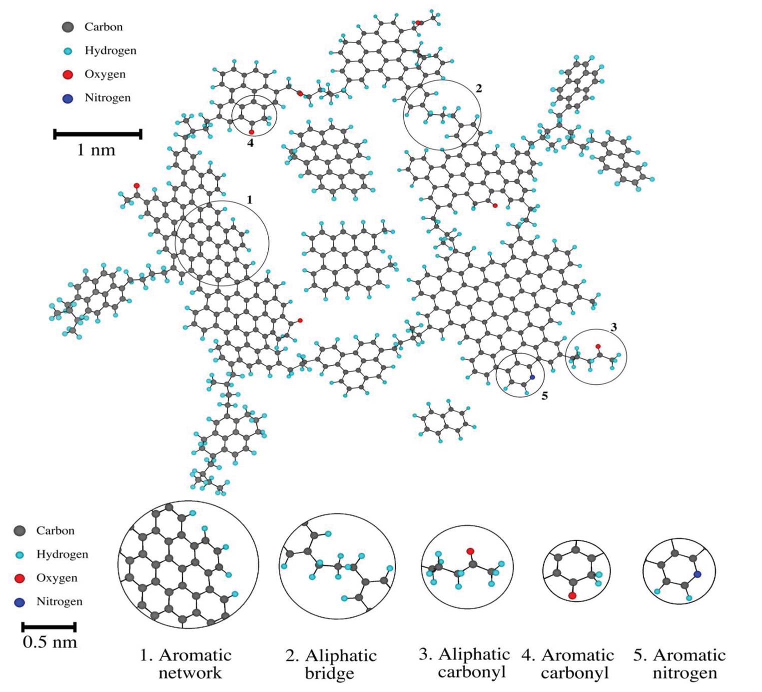
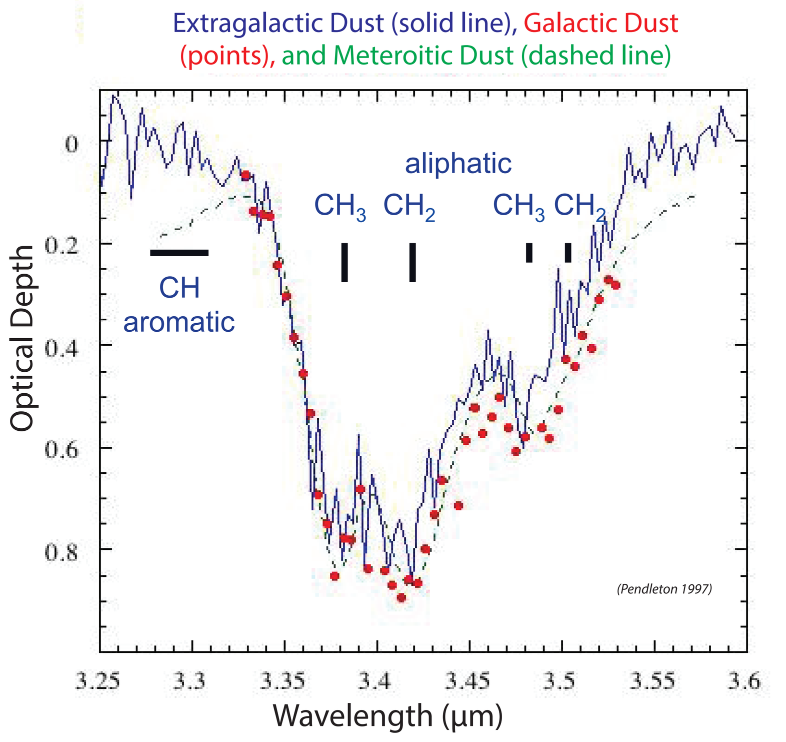
Diffuse interstellar medium grain fragment



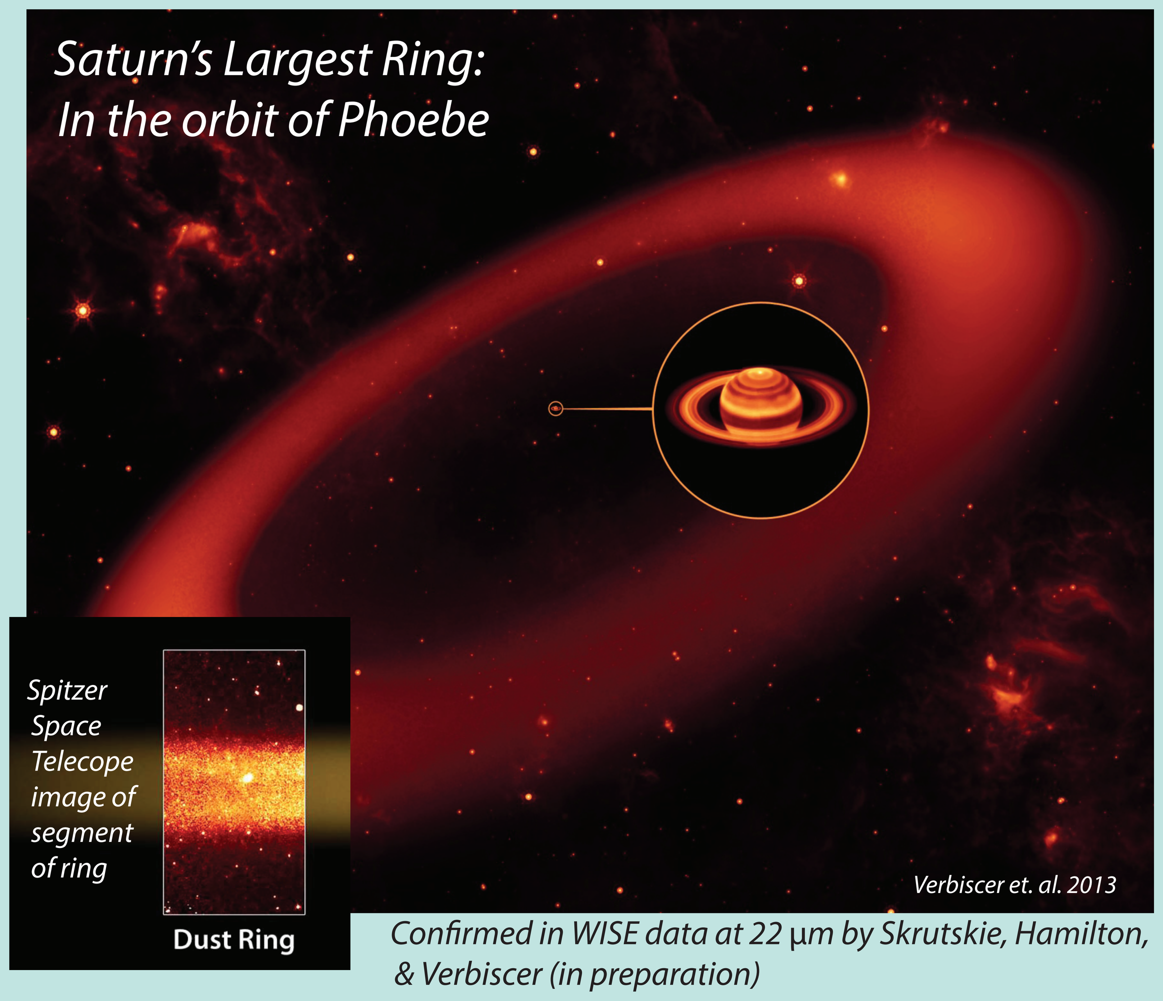
From Pendleton, Y. J. and Alamandola, L. J. (2002). The Organic Refractory Material in the Diffuse Interstellar Medium: Mid-IR Spectroscopic Constraints. *Astrophys J. Supp.* Ser., 138, 75-98.

The basic structural and molecular character of carbonaceous, interstellar dust in the DISM, from Pendleton and Allamandola (2002). The structure and specific geometrics of the aromatic plates and aliphatic components are notional, but the relative numbers of aromatic and aliphatic carbon-hydrogen bonds, as well as their subclassification within type, are all consistent with the observed spectra of the interstellar dust. A typical 0.1-µm carbonaceous interstellar dust grain would contain ~10⁴ of these fragments.



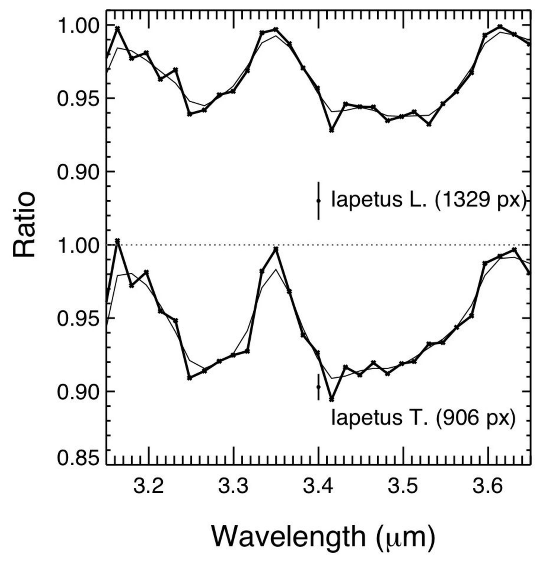
Absorption bands observed near 3.4 µm through the DISM have been attributed to aliphatic (chain-like) hydrocarbons with functional groups in the abundance ratio of CH_2 / CH_3 ~2.5. Comparisons of the galactic and extragalactic spectra (Pendleton et al 1994 and Wright et al 1996, respectively) to the sublimate from the acid-insoluble residue of the Murchison meteorite (DeVries et al 1993) reveal correlations in peak positions, widths, and profiles. Mennella (2010) found that CH_2 and CH_3 aliphatic vibrational modes are activated at the end of H processing in laboratory samples, supporting an evolutionary connection between the interstellar carbon grain population in diffuse and dense regions, interplanetary dust particles, and cometary *Stardust* grains.

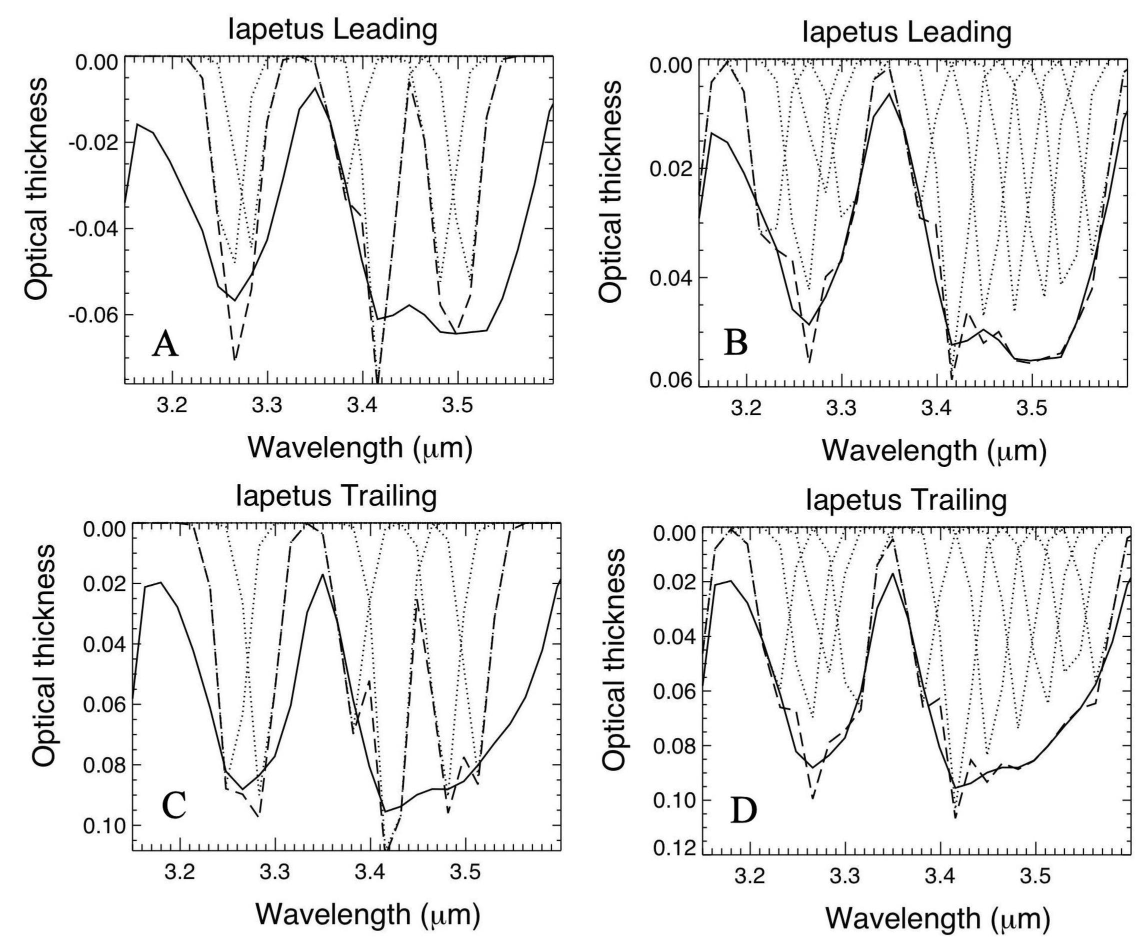
Dust ejected from a collision on Phoebe spirals toward Saturn and coats the surfaces of Iapetus (leading hemisphere) and Hyperion (Tamayo et al., 2011)



Confirmed in WISE data at 22 µm by Skrutskie, Hamilton, & Verbiscer (in preparation)

Reflectance spectra of low-albedo surface material on the leading (L) and trailing (T) hemispheres of Iapetus, from Cassini VIMS data. The absorption envelope on the left (3.15-3.35 µm) represents aromatic hydrocarbons, while the absorption on the right (3.35-3.60 µm) of the peak arises from aliphatic hydrocarbons.

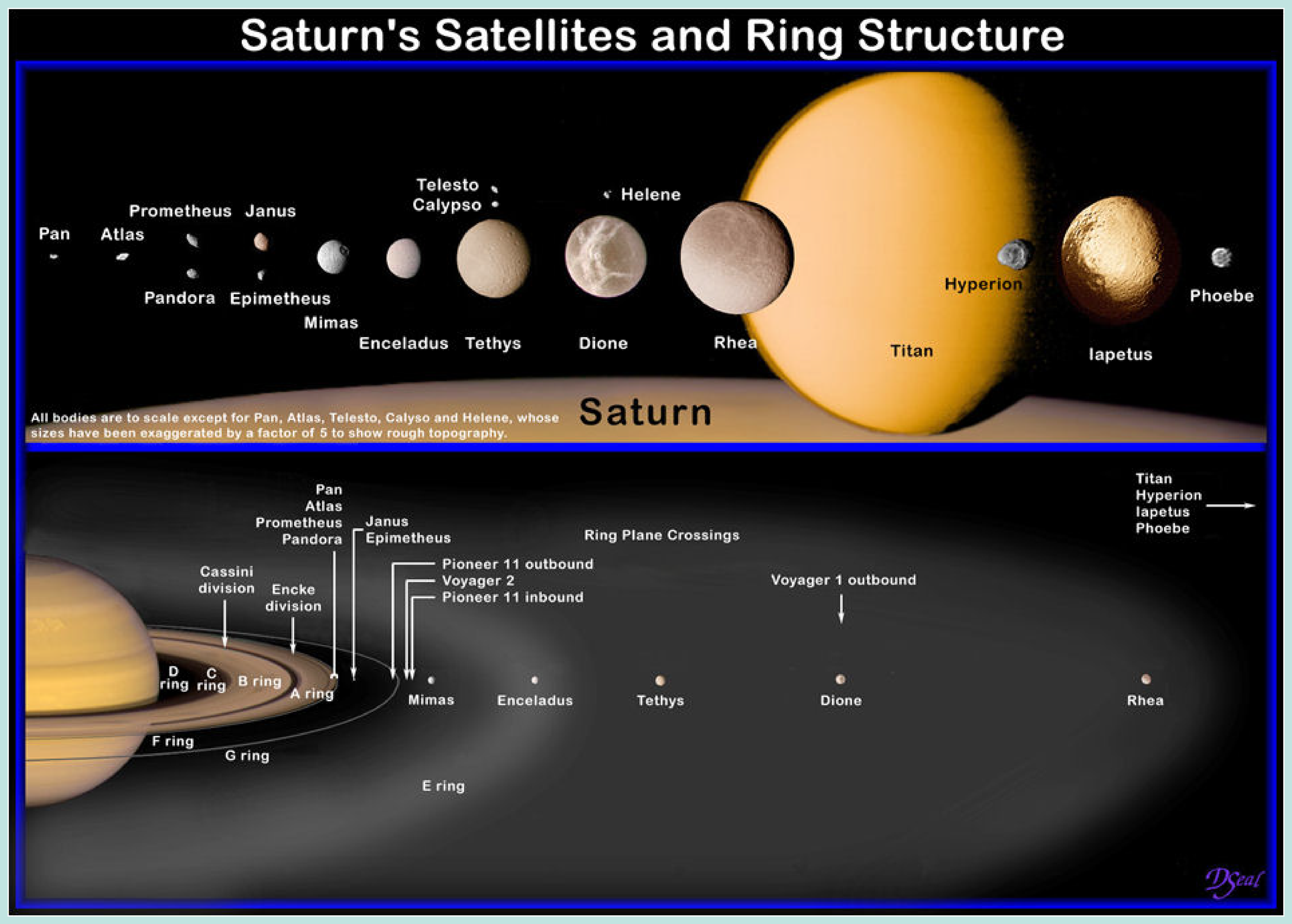




Gaussian deconvolution of Iapetus spectra shown above. Two examples are given for each spectrum; one is a minimal fit of Gaussians corresponding to known molecular groups, and one consists of a plausible set of Gaussians that more fully fill the aromatic and aliphatic absorption envelopes.

Quantitative analysis of the hydrocarbon spectral bands on Iapetus demonstrates that aromatic CH is ~10 times as abundant as aliphatic CH_2+CH_3, significantly exceeding the strength of the aromatic signature in interplanetary dust particles, comet particles, and in carbonaceous meteorites (Cruikshank et al. 2013). A similar excess of aromatics over aliphatics is seen in the qualitative analysis of Hyperion and Phoebe itself (Dalle Ore et al. 2012). The Iapetus aliphatic hydrocarbons show CH_2/CH_3 ~4, which is larger than the value found in the diffuse ISM (~2-2.5). However, Matrajt et al (2013) report CH_2/CH_3 ratios as high as 4.6 for an interplanetary dust particle and 4.3 for one of the comet Wild 2 particles analyzed in that paper.

Saturn's Satellites and Ring Structure



"Complex chemical reactions occur in the solar nebula as ice-mantled grains diffuse to different regions."
-- Ciesla and Sandford, *Science*, April 2012

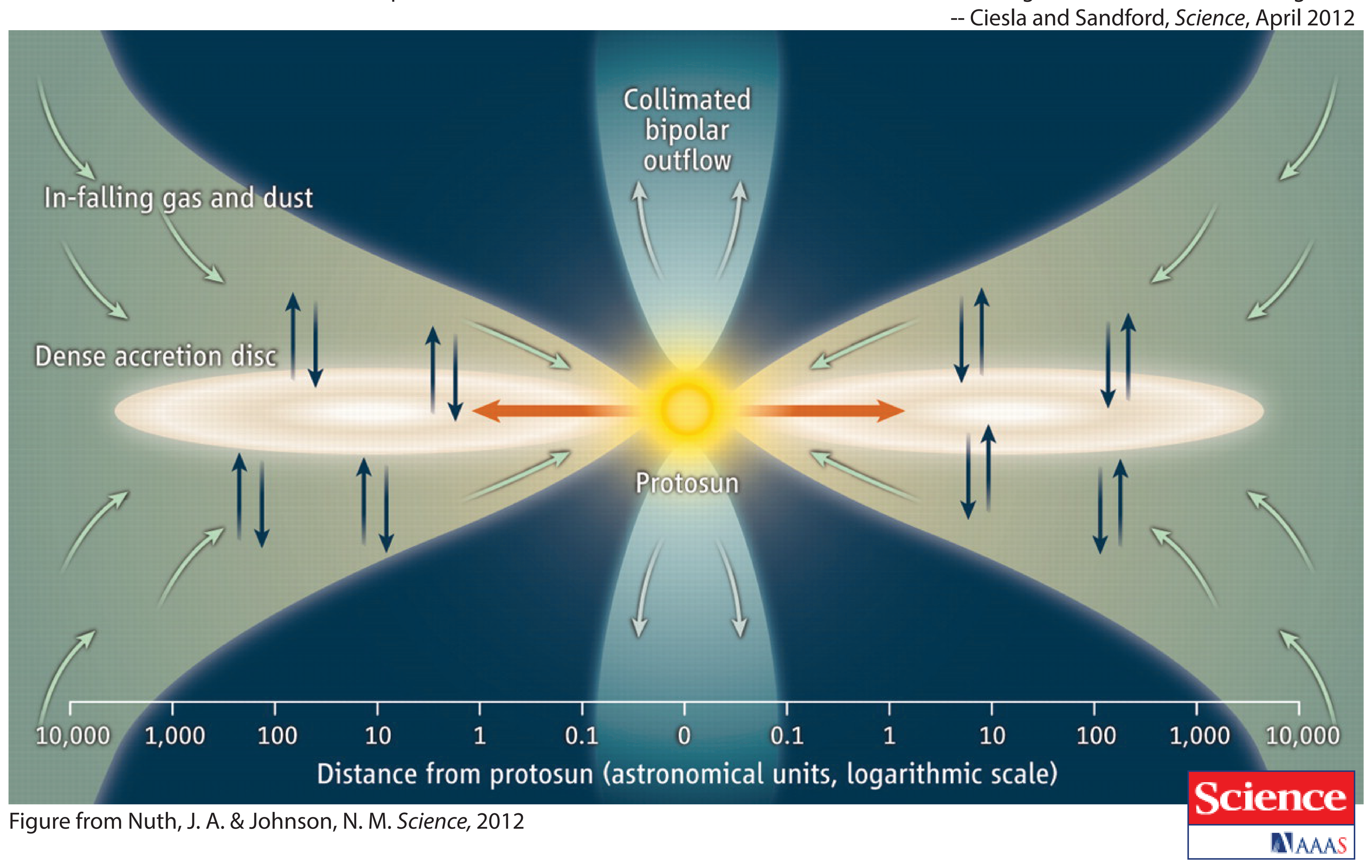


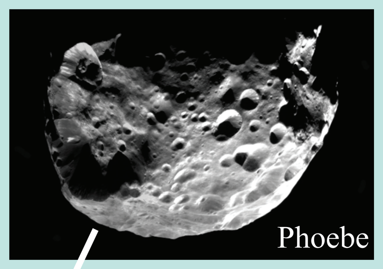
Figure from Nuth, J. A. & Johnson, N. M. *Science*, 2012

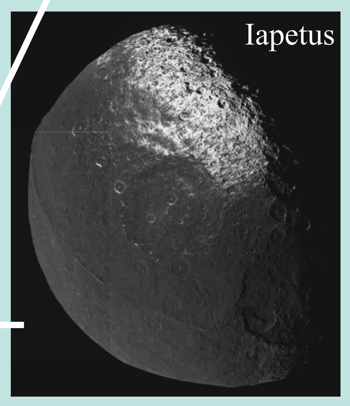
Some possible pathways for organics in the Solar System

- Interstellar aliphatics (and possibly aromatics) may have survived unchanged during planetesimal formation
- Aromatics may have formed through conversion of aliphatics (e.g., shock formation during impact on Phoebe that liberated the dust)
- Perhaps aromatics and aliphatics both formed in solar nebula, then were incorporated into planetesimals

Three Saturnian Satellites

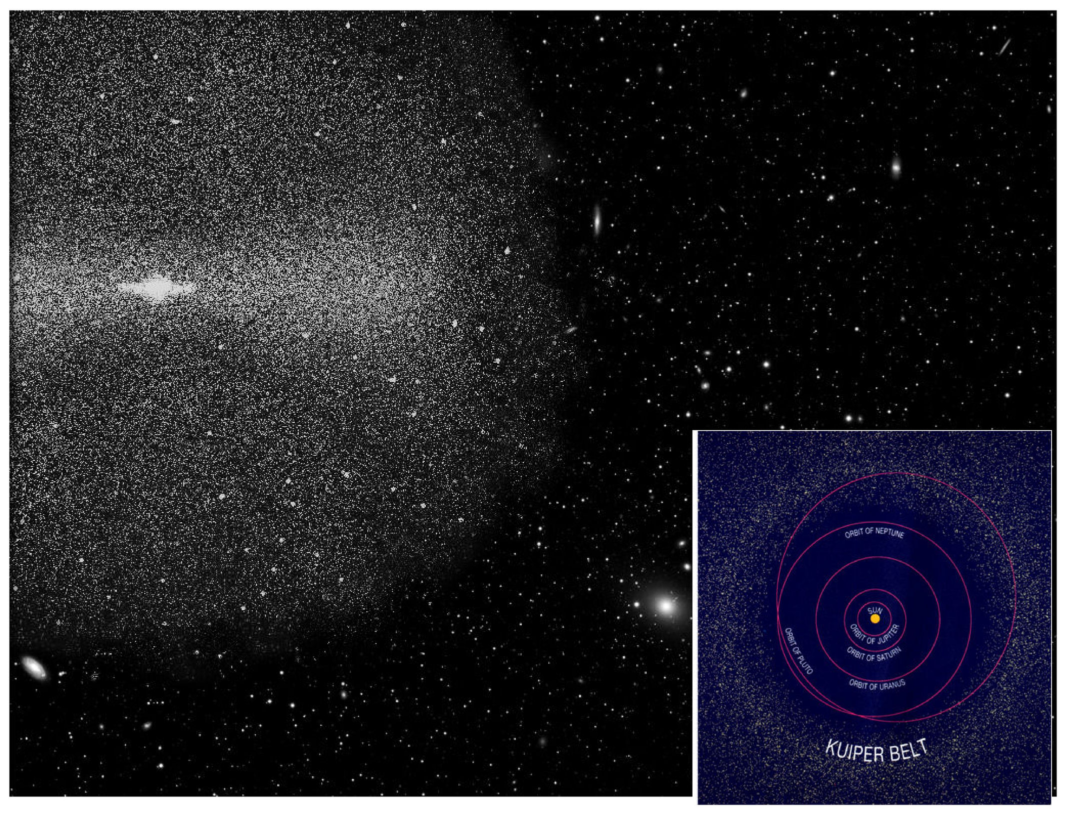
	Diameter (km)	Density (g/cm³)	Notes
Phoebe	213	1.63	Retrograde, inclined orbit. Captured
Iapetus	1470	1.08	Locked synchronous rotation
Hyperion	266	0.57	Chaotic rotation. Low density





Conclusions

Insofar as Phoebe is a primitive body that formed in the outer regions of the solar nebula and may have preserved some of the original nebula organic inventory, it can be a key to understanding the content and degree of processing of that nebular material. There are other Phoebe-like TNOs that are presently beyond our ability to study in the organic spectral region, but JWST will open that possibility for a number of objects. We now need to explore and understand the possible connection of this organic-bearing Solar System material to the solar nebula and the inventory of ISM materials incorporated therein.



Planetesimals condensed in the outer Solar System and became the bodies that now comprise the Kuiper Belt. In this diagram the Kuiper Belt is the disk shown edge-on, surrounded by the spherical Oort Cloud. Inset: Kuiper Belt and planet orbits in plan view.

Phoebe as a Kuiper Belt Object

- Captured by Saturn (retrograde, inclined orbit)
- Carries an unusual organic inventory
- Contains CO_2 as an original component
- A new class of CO_2-rich comets has been identified (e.g., 103P/Hartley 2) --Phoebe may be a former member of this class
- Density (1.6 g/cm³) consistent with formation in the outer solar nebula in a CO-rich region (i.e., oxidizing environment) (T. Johnson, J. Lunine)
- Currently not possible to observe other Kuiper Belt objects in the organic spectral region with sufficient sensitivity to detect any absorption bands that might exist.

Summary

- *Cassini* data on the Saturn satellites provide a unique view of organics in Solar System materials, as do new more complex chemical models of the proto-solar nebula
- New data show spectral signatures of aliphatics and aromatics on three Saturnian satellites, with aromatics significantly more abundant
- Organics on Saturn satellites invite a new look at aromatic and aliphatic hydrocarbons in meteorites, IDPs, *Stardust* particles, their points of origin and subsequent histories

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